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Abstract

Saccadic eye movements were studied in six subjects during two Space Shuttle missions. Reaction time, peak velocity and accuracy of horizontal, visually-guided saccades were examined preflight, in flight and postflight. Conventional electro-oculography was used to record eye position, with the subjects responding to pseudo-randomly illuminated targets at 0° and $\pm 10^\circ$ and 20° visual angles. In all subjects, preflight measurements were within normal limits. Reaction time was significantly increased in flight, while peak velocity was significantly decreased. A tendency toward a greater proportion of hypometric saccades in flight was also noted. Possible explanations for these changes and possible correlations with space motion sickness are discussed.

Introduction

Neurologic adaptation to space flight was studied during a joint Johnson Space Center Flight Operations Directorate and Medical Sciences Division investigation on Shuttle missions STS-4 through 8 (1982-3) (1). As part of this comprehensive study, eye motions were examined under various experimental conditions including vestibulo-ocular and optokinetic reflexes. The results of investigations on the saccadic system are presented here. Preflight, in-flight and postflight measurements were obtained from six subjects on STS-7 and 8 (June and August 1983). Effects of weightlessness, susceptibility to and the actual presence of space motion sickness (SMS) on the latency, peak velocity, and accuracy of horizontal saccades were examined.

The neurologic system necessary for the generation of purposeful saccades has been investigated in animals and human patients. It is believed that the program for visually-guided saccades is initiated in the frontal eye fields (2), and reaches the saccadic pulse generator in the pontine reticular formation via the superior colliculus (3,4,5), where the saccade's velocity and amplitude may be determined (6). There is also evidence for input to the pontine generator from the posterior parietal cortex (7) and the cerebellum (8), as well as for an inhibitory input from the substantia nigra (9). The saccade is effected by signals reaching the extraocular muscles from the oculomotor nuclei in the brainstem (10).

Saccadic parameters can be affected by natural factors such as circadian rhythm (11) or fatigue (12) and other factors such as drugs (13) or central nervous system (CNS) pathology (14,15). Latency or reaction time depends on several factors including age (16), motivation (17), stimulus parameters (18), afferent visual system (19), and ocular motor efferent system (10). Peak velocity is characteristically related to the amplitude of the saccade (20,21), although considerable physiological inter- and

intra-subject variability exists within this main sequence relationship (21).

Disturbances in the system responsible for saccadic eye movements can potentially affect their latency, velocity, or accuracy. It is possible that effects of weightlessness are mediated directly by the vestibular system. It has also been speculated that the known cephalad fluid redistribution caused by exposure to weightlessness (22) may bring about altered CNS function (23). It is therefore appropriate to study the saccadic system during space flight for any effects of weightlessness. In addition, it is of interest to see if susceptibility to or the presence of SMS independently alters saccades.

Vesterhauge *et al.* (24) reported on visually-guided saccades in nine subjects during parabolic aircraft flights, which produce brief periods (10-30 seconds) of weightlessness alternating with periods of hypergravity. Using methodology similar to that reported here, they found significantly longer latencies and a nonsignificant tendency toward higher velocities during the weightless phases of the flights.

Saccadic velocity was discussed in two reports of eye-head coordination during space flight. In the first investigation of a single primate, saccadic velocity along with saccadic amplitude was markedly increased during flight (25), while the second study of four human subjects showed markedly decreased saccadic amplitudes and velocities during space flight (26). Different experimental protocols and the lack of constant saccade amplitudes makes comparison of these studies difficult. In addition, the mechanisms that generate saccades during head movements may not be the same as those that produce visual saccades (27).

Methods

Subjects. The six volunteer subjects for this study were all professional male NASA astronauts, ranging in age from 34 to 54 years. All had experience in high-performance jet aircraft and one had prior space flight experience. There were no known or detectable visual abnormalities other than presbyopia corrected to normal acuity by glasses. Consent was obtained from each subject after explanation and demonstration of the procedure. A physician crewmember on each flight administered the test following a standardized checklist. The only medication taken involved two of the subjects who were participating in a concurrent study of metoclopramide during the first two flight days.

EOG recording. Horizontal eye movements were recorded using conventional electro-oculography (EOG) methods (28). One cm Ag-AgCl electrodes were located at the lateral canthi with a mid-forehead ground. Amplification was either DC or AC coupled with a low frequency response

to 0.05 Hz (3 dB). Accuracy of eye position was better than 2%. The EOG and target synchronization signals were recorded and replayed on an FM cassette tape system. Overall high frequency response, including demodulation was greater than 100 Hz.

The signals were displayed graphically on a Gould ES-1000 electrostatic recorder, providing a high-frequency response of <0.1 msec. Recording speed of 100 mm/sec allowed a time resolution of ± 5 msec, with crystal-controlled timing grid allowing calibration of paper speed.

Protocol. The subjects viewed a horizontal array of five high-intensity light-emitting diodes (LEDs) located at visual angles of 0°, 10° and 20° right and left of center. Each LED subtended 0.3° of arc at a viewing distance of 1.8 m. They were switched in a pseudo-random fashion at a frequency of 1/sec, the center target lighting after each eccentric deflection. A minimum of ten deflections were performed during each test run, and each run was repeated at least once during each recording session.

Data reduction and analysis. Graphic records were analyzed for the following saccade parameters: latency, peak velocity, and accuracy (figure 1). Saccadic reaction time was measured from the onset of the eccentric LED switching to the onset of the saccadic eye movement response, defined as the first detectable movement away from baseline on the EOG tracing. Trials in which the subject made anticipatory saccades to the wrong target, or responded in less than 100 msec were excluded from the analysis. Saccade latencies greater than 500 msec were excluded on the basis of likely inattention.

Peak velocity of each eccentric saccade was determined by measuring the maximum slope of the EOG tracing using a Houston Instruments HIPAD digitizer on-line with an IBM-XT personal computer and SigmaScan (Jandel Scientific) software package.

Accuracy of the saccadic eye movements was assessed by determining the proportion of all saccades that did

not require a secondary movement to reach the desired target. No attempt was made to determine the mean amplitude gain of the saccades.

Each saccade parameter was analyzed by first determining an overall mean for all saccades. Then, means were calculated for all 10° and 20° saccades and for all leftward and rightward saccades. Means were also determined for preflight and in-flight saccades, and when possible, for the SMS susceptible and non-susceptible populations.

In-flight operational constraints precluded consistent data sampling times among the subjects. In order to differentiate between early and late adaptation to space flight, in-flight data points were combined into an early epoch (Mission Day [MD] 1-2) and a late epoch (MD 3-5), and each compared to preflight values. Four of the six subjects produced sufficient data to meet these criteria. The other two subjects were included in a further analysis comparing preflight and all in-flight data.

The General Linear Models procedure in the Statistical Analysis System (SAS) software package was used to determine statistical relations (29). Multivariate analysis of variance (30) and analysis of variance of contrast variables allowed comparisons between preflight and in-flight measurements, between saccade parameters, and between SMS susceptible and non-susceptible populations.

Results

Table 1 shows the number of records and days on which they were obtained for each subject. There was a total of 42 records, of which 22 were preflight, 15 during flight, and 5 postflight. None of the subjects reported any subjective visual or oculomotor disturbances during the flights. The three subjects marked with an (*) exhibited symptoms of SMS on MD 1 and 2; five records were obtained during their symptomatic period. Due to technical problems at the landing site, only saccadic velocity data were available from the postflight recording session.

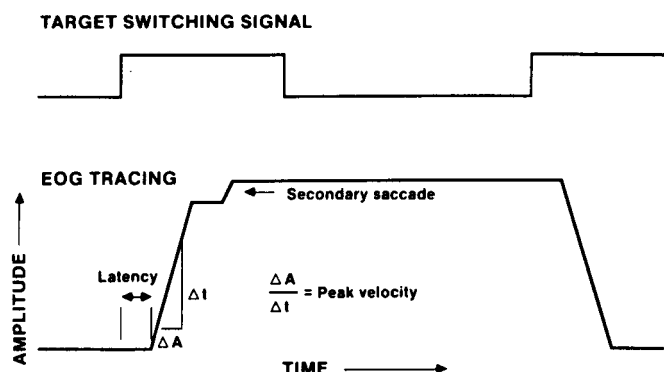


Figure 1.— Schematic representation of saccadic eye movement recording to illustrate data reduction.

Table 1.— Schedule of records obtained

Subject	Preflight	Inflight Mission Day					Postflight
		1	2	3	4	5	R+1H
1*	2	1	1	1	1	1	
2	3	1					1
3	3	1					1
4*	3	1	1		1		1
5	4	1				1	1
6*	7	1			1		1

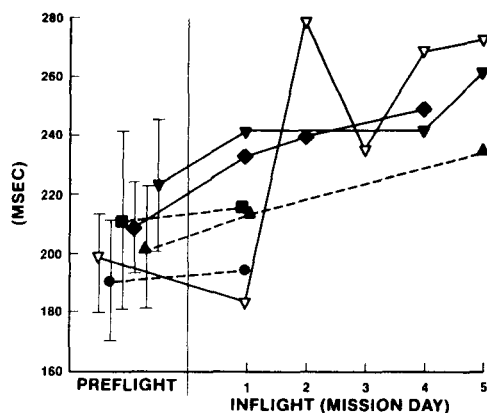


Figure 2.— Mean latency of saccadic eye movements of six subjects as a function of flight phase. Solid lines denote SMS susceptible subjects and dashed lines represent non-susceptible individuals.

Latency. All subjects had preflight latencies in the range of 200 msec (mean \pm S.D.=196 \pm 9 msec), which agrees with other investigators' results (10,31). With one exception (one subject on MD 1 had a decreased latency), all subjects had longer reaction times during space flight, with a general trend toward increasing latencies as the flight progressed (figure 2).

In the four-subject population with recordings in both in-flight epochs, a statistically significant ($p=0.0164$) increase in latency was seen with increasing flight duration. Preflight mean \pm S.D. for the four subjects was 198 \pm 9 msec, increasing to 218 msec for the MD 1-2 epoch and to 239 msec for the MD 3-5 period. Despite reports in the literature suggesting that for saccades smaller than 20° latency remains fairly constant (32), we found a significantly longer ($p=0.0016$) reaction time for 20° than for 10° saccades. No left-right asymmetry in latency was observed.

For the larger group of six subjects, mean in-flight latency was significantly increased over the preflight mean (table 2). Latencies of 20° saccades were significantly longer than latencies of 10° saccades, but no directional asymmetry was observed. No preflight difference was noted between the SMS susceptible and non-susceptible groups, but the affected population had

Table 2.— Summary of statistical results of saccade latencies

Parameter	Mean value (msec)	p = —
10 deg vs. 20 deg	194 vs. 222	0.0074
Left vs. Right	209 vs. 208	0.9651
Pre- vs. Inflight	195 vs. 218	0.0125
SMS vs. non-SMS	218 vs. 198	0.0714

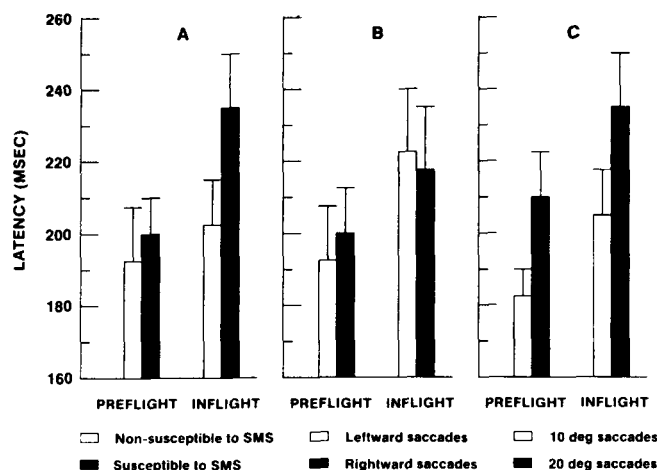


Figure 3.— Preflight and inflight mean and S.D. of saccade latencies of the six-subject population, examined with regard to susceptibility to SMS (A), directional symmetry (B), and amplitude of saccades (C).

prolonged reaction times in-flight (figure 3 [A]). Mean leftward and rightward saccade latencies were each increased by approximately the same amount in-flight (figure 3 [B]), as were mean 10° and 20° saccade reaction times (figure 3 [C]).

Velocity. Individual responses of the six subjects' saccade velocities are shown in figures 4(a) and 4(b). All measurements fell within published main sequences (12,14,20,21). A trend in most subjects toward slower saccade velocities in-flight, for both 10° and 20° deflections, is apparent. Of the five subjects who also performed postflight measurements one hour after landing, most had saccade velocities that had returned to within one standard deviation of their preflight mean. One subject, who had a notable decrease of all his in-flight velocities, maintained the decrease postflight.

In the population of four subjects who made recordings during both in-flight epochs, overall mean saccade velocities were significantly greater ($p=0.0167$) for 20° than for 10° deflections. Comparing overall preflight and in-flight measurements, the observed individual tendency toward slower saccades did not reach significance at the $p=0.05$ level. Only when isolating the 10° saccades to the right was there a significant ($p=0.003$) decrease in velocity in-flight. No significant difference was noted between the velocity of leftward versus rightward saccades.

In the larger population of six subjects, overall there were significant differences in velocity, between preflight and in-flight measurements, and between SMS susceptible and non-susceptible groups for both 10° and 20° saccades (table 3). Upon further examination, it can be

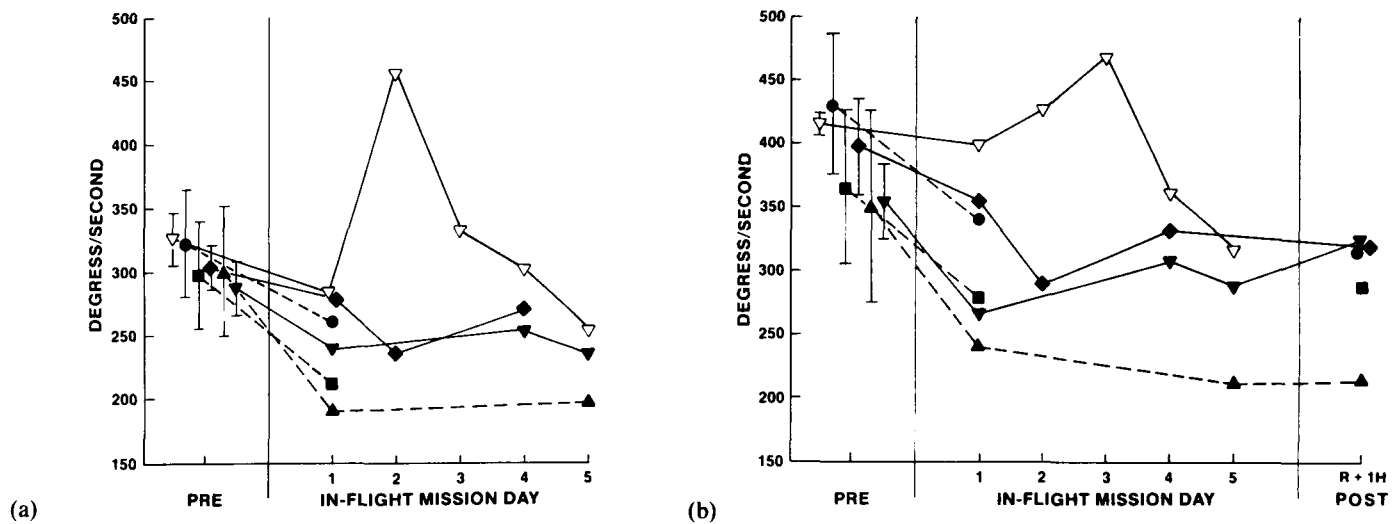


Figure 4.— Mean peak velocity of 10 degree (a) and 20 degree (b) saccades of six subjects as a function of flight phase. Solid lines denote SMS susceptible subjects and dashed lines represent non-susceptible individuals.

seen that while the two groups had similar velocities preflight, those not susceptible to SMS reduced their in-flight velocities to a greater extent (24.2%) than the susceptible group (8.2%) (figure 5 [A]). In-flight decreases in the velocity of saccades were comparable for both directions (figure 5 [B]) and for both amplitudes (figure 5 [C]).

Accuracy. Preflight, the accuracy of saccades varied greatly among the subjects, the range of accurate saccades being 39.0% to 84.7%. All inaccurate saccades were due to undershooting, with no hypermetric saccades being recorded at any time. In-flight changes in the accuracy of saccadic eye movements were somewhat variable among the six subjects. It appears that there was a slight tendency to increased accuracy early in-flight, followed by a decreasing trend (figure 6).

Table 3.— Summary of statistical results of saccade velocities

Parameter	Mean value (deg/sec)	p = ____
10 deg		
Left vs. Right	288 vs. 274	0.0544
Pre- vs. Inflight	304 vs. 258	0.0042
SMS vs. non-SMS	294 vs. 269	0.0489
20 deg		
Left vs. Right	358 vs. 347	0.3465
Pre- vs. Inflight	387 vs. 320	0.0016
SMS vs. non-SMS	372 vs. 334	0.0194

In the six subjects, mean accuracy decreased non-significantly in-flight, with an overall proportion of 50.8% on-target saccades compared to 57.8% preflight. The overall difference in the proportion of on-target saccades between SMS susceptible and non-susceptible groups was significant ($p=0.0477$) (figure 7 [A]), as was the difference between all leftward and rightward directed saccades ($p=0.0401$). This appears to be due primarily to significant asymmetry that was present preflight but disappeared in-flight (figure 7 [B]). There was a significantly ($p=0.0401$) greater proportion of hypometric saccades during 20° deflections than during 10° deflections (figure 7 [C]).

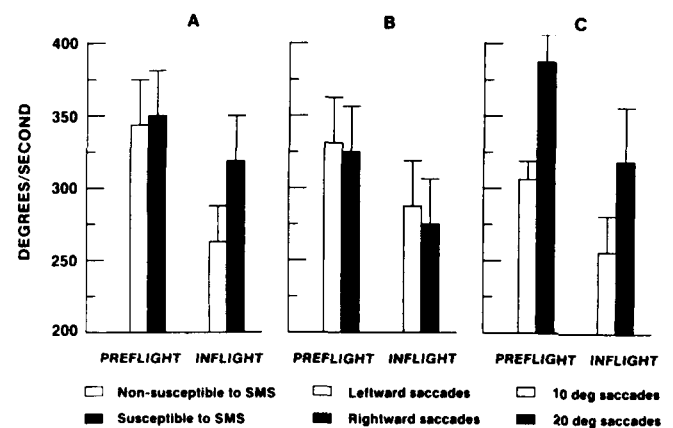


Figure 5.— Preflight and inflight mean and S.D. of saccade peak velocities of the six-subject population, analyzed with regard to susceptibility to SMS (A), directional symmetry (B), and amplitude of saccades (C).

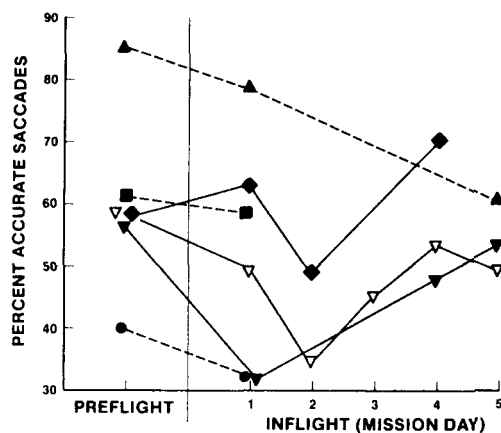


Figure 6.— Accuracy of saccadic eye movements, expressed as percent of all saccades that were on-target, of six subjects as a function of flight phase. Solid lines denote SMS susceptible subjects and dashed lines represent non-susceptible individuals.

Discussion

To our knowledge, this is the first study of saccadic eye movements in humans during space flight. We have shown that it is possible to obtain reliable physiologic data from crewmembers during shuttle flights that are not dedicated life sciences missions. Although operational constraints limited the amount of data collected, certain conclusions can be drawn about the response of the saccadic system to space-flight conditions.

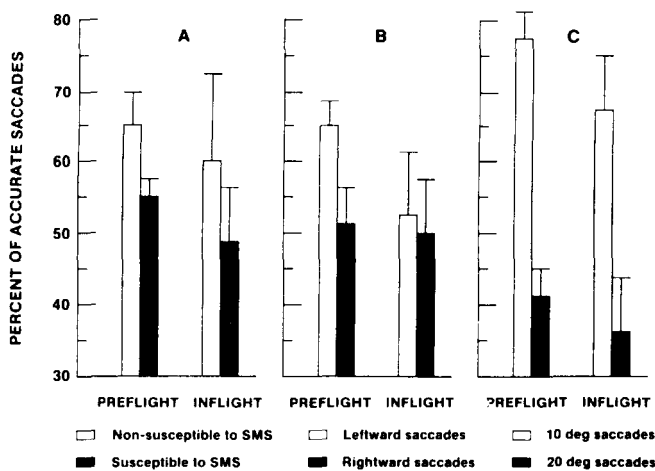


Figure 7.— Preflight and inflight mean and S.D. of saccade accuracy, expressed as the percent of all saccades that were on-target. The six-subject population is examined with regard to susceptibility to SMS (A), directional symmetry (B), and saccade amplitude (C).

Among the significant inflight changes observed were a prolonged reaction time and a reduced peak velocity of saccades, as well as a tendency toward decreased accuracy. The mean changes were small, amounting to an 11.8% increase in latency, a 16.7% decrease in velocity and a 16.6% decrease in the proportion of accurate saccades. The clinical or functional significance of the changes is unclear. They had no apparent effect on any of the subjects, all of whom denied visual or oculomotor disturbances or degradation of performance. All crewmembers executed without apparent difficulty a multitude of operations requiring good oculomotor performance.

Poor motivation, fatigue or inattention could lead to such findings, and arguably may have contributed to the results. Several factors make this explanation unlikely. First, the subject population under study (NASA astronauts) is, by selection and training, likely to remain highly motivated under demanding conditions. Second, measurements from five subjects made one hour after landing, usually a time of increased crew fatigue, were nearly all within preflight norms. And third, at least with regard to reaction time, saccades with excessively long latencies due to inattention were eliminated from consideration.

It is also unlikely that either weightlessness-induced fluid shifts or altered CNS function (primary or secondary to fluid shift) caused the observed changes in saccade parameters. The fluid redistribution affects all individuals soon after exposure to weightlessness, and appears to reach an equilibrium thereafter (22). The trends we observed continued throughout the flight.

Altered CNS function can potentially affect saccades (19,33,34). Although small individual changes in visual acuity and contrast sensitivity during space flight have been reported, no population trends have been noted (35,36). Based on the results of other space-flight investigations, such as normal auditory evoked potentials and the absence of abnormal nystagmus (37), there is no evidence to indicate a disruption of CNS function during space flight.

Although gross CNS pathology can be ruled out in this case, more subtle and adaptive changes may be involved. Comparing a group of patients with tension headaches and normal subjects, Carlsson and Rosenhall (38) observed that saccadic velocities were about 10% slower in the patients, none of whom had any demonstrable neurologic deficit. They attributed this difference to abnormal proprioceptive signals generated by muscle tension in the neck of the patients, affecting oculomotor function via the cervico-ocular reflex (COR).

There is no direct evidence to link the COR to the saccadic velocity changes seen in our study. However,

increases in the height of subjects during space flight have been documented (39,40), presumably due to expansion of the intervertebral spaces. This may result in altered proprioceptive signals from those receptors in the cervical intervertebral joints and ligaments (41) believed to be involved in the COR (42), which, in turn, influences oculomotor function. A single in-flight measurement of COR gain in one of the subjects in this study was in the usually reported range of 0.02 (unpublished observation).

What is the correlation, if any, between the observed changes in saccadic eye movements and SMS? Commonly reported symptoms of SMS include somnolence, malaise and lethargy (1), which could be expected to delay and slow saccades. Therefore, it would not be unreasonable to predict longer latencies, slower velocities, and perhaps less accurate saccades in affected individuals.

Based on our mean statistical data, this may initially appear to be the case. There are the expected differences between the SMS susceptible and non-susceptible populations. However, it must be remembered that each group was small ($n=3$). Furthermore, there was at least one individual who, during his symptomatic period (MD 1 and 2), exhibited what may be an idiosyncratic response: decreased latency and increased peak velocity (figures 2 and 4). Finally, latency remained elevated throughout the flight, even though all subjects had recovered from SMS.

We are aware of one other report on visually-guided saccades during brief exposure to weightlessness (24). Although their experimental protocol was similar to ours, they used parabolic aircraft flights, during which brief periods (10-30 seconds) of weightlessness alternate with hypergravity, as their study environment. In addition, they utilized a different study population. In their nine subjects, latency was significantly increased and velocity nonsignificantly increased during the weightless phases of the flights.

Several explanations may account for the conflicting results. First, small population effects, where one or two subjects' results can dramatically alter overall findings. This may be significant in light of the one subject in our study who appears to have demonstrated an idiosyncratic

response. Second, the short-lived and hypergravity-interrupted weightlessness of parabolic flight is not equivalent to the long-term weightlessness of space flight. And third, their observed changes occurred over the range of seconds to minutes and reflect acute changes, while ours took place over hours to days and represent a more long-term adaptation.

It is difficult to compare our results with those of the other two space-flight reports on saccadic velocities. Both of them involved measuring saccades as part of eye-head coordination studies, and saccadic amplitudes (and therefore velocities) were not constant. Their apparently contradictory findings may in part be explained by the fact that the primate study used specific visual targets (25), while the human study did not (26). Visual and non-visual saccades show different velocity characteristics (17), and may have different underlying mechanisms (27).

In conclusion, as part of a dedicated study of saccadic eye movements during space flight, the results from six subjects indicate a statistically significant increase in saccadic latency, a decrease in saccadic velocity, and a tendency toward a greater number of inaccurate saccades. Any correlation between changes in saccadic eye movements and space motion sickness remains in question because of possible diverse individual reactions. Further confirmation of the observed changes and their time course awaits future study, as does elucidation of the possible underlying mechanisms.

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Appendix — Data Tables

Table A1 - Preflight saccade parameters

	Latency, msec	Peak velocity, deg/sec	Accuracy ¹ , %
Subject 1			
L-11 days	215±31	316±45	42.9
L-20 days	191±57	373±68	61.8
Subject 2			
L-49 days	209±45	274±44	46.7
L-35 days	198±26	297±48	46.7
L-14 days	163±46	467±65	25.8
Subject 3			
L-42 days	245±85	347±49	47.1
L-35 days	214±58	283±56	60.0
L-14 days	182±55	386±54	62.7
Subject 4			
L-49 days	223±118	297±45	46.7
L-36 days	215±44	268±46	50.0
L-14 days	187±56	489±76	76.0
Subject 5			
L-49 days	200±64	292±56	69.6
L-35 days	203±64	262±42	90.3
L-33 days	171±50	383±57	85.0
L-14 days	231±45	306±132	80.0
Subject 6			
L-57 days	212±46	281±52	50.8
L-49 days	209±69	355±92	69.2
L-42 days	238±69	278±44	56.5
L-40 days	225±52	286±46	46.8
L-35 days	247±51	266±48	54.2
L-33 days	188±50	392±83	51.8
L-14 days	248±57	288±62	38.8

¹Expressed as the percent of all saccades that are accurate.

Table A2.— Latency of saccades (msec)

Subject	Preflight	Inflight Mission Day				
		1	2	3	4	5
1	198±14	183	278	235	268	272
2	190±20	194				
3	210±30	215				
4	208±15	232	239		248	
5	201±21	213				234
6	222±22	241			241	261

Table A3.— Peak velocity of saccades (deg/sec)

Subject	Preflight	Inflight Mission Day					Postflight R+1H
		1	2	3	4	5	
1	360±42	346	435	405	340	285	
2	362±104	299					315
3	315±75	233					286
4	351±98	314	258		301		319
5	311±45	224				203	213
6	309±55	251			280	261	322

Table A4.— Accuracy of saccades¹

Subject	Preflight	Inflight Mission Day				
		1	2	3	4	5
1	58.0	48.8	33.3	43.6	52.6	48.5
2	39.0	31.8				
3	60.2	57.6				
4	57.1	62.5	48.0	68.7		
5	84.7	77.8	59.5			
6	55.4	31.0	46.9	52.4		

¹Expressed as the percent of all saccades that are accurate

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16. Abstract Saccadic eye movements were studied in six subjects during two Space Shuttle missions. Reaction time, peak velocity and accuracy of horizontal, visually-guided saccades were examined preflight, inflight and postflight. Conventional electro-oculography was used to record eye position, with the subjects responding to pseudo-randomly illuminated targets at 0° and ± 10° and 20° visual angles. In all subjects, preflight measurements were within normal limits. Reaction time was significantly increased inflight, while peak velocity was significantly decreased. A tendency toward a greater proportion of hypometric saccades inflight was also noted. Possible explanations for these changes and possible correlations with space motion sickness are discussed.					
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